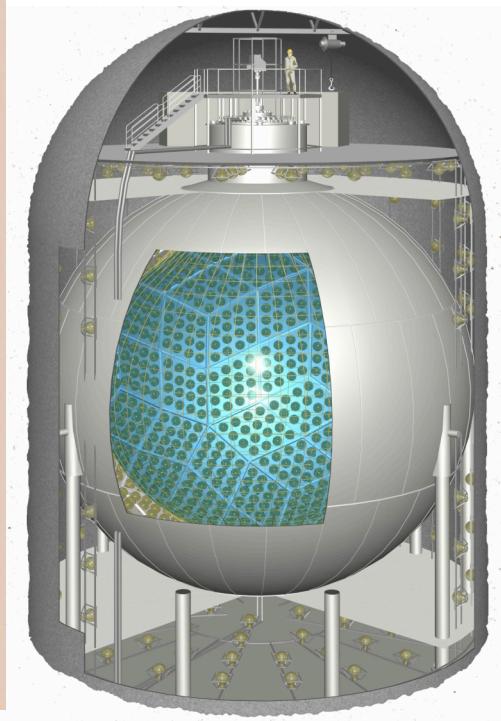
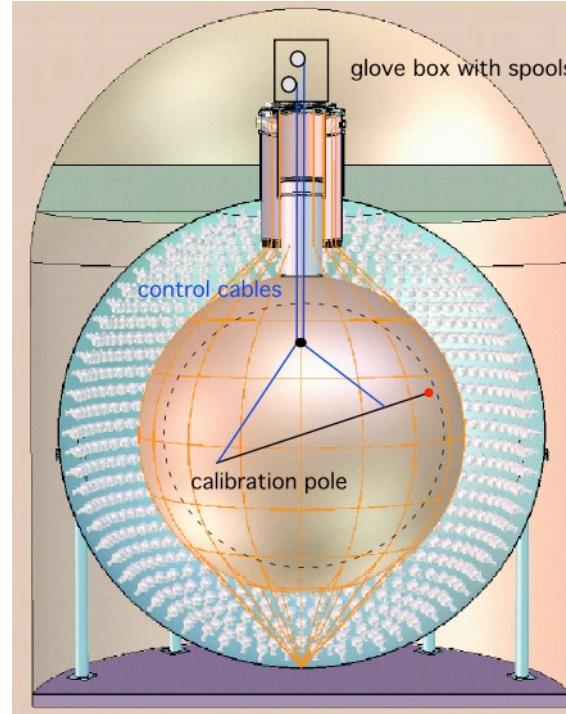
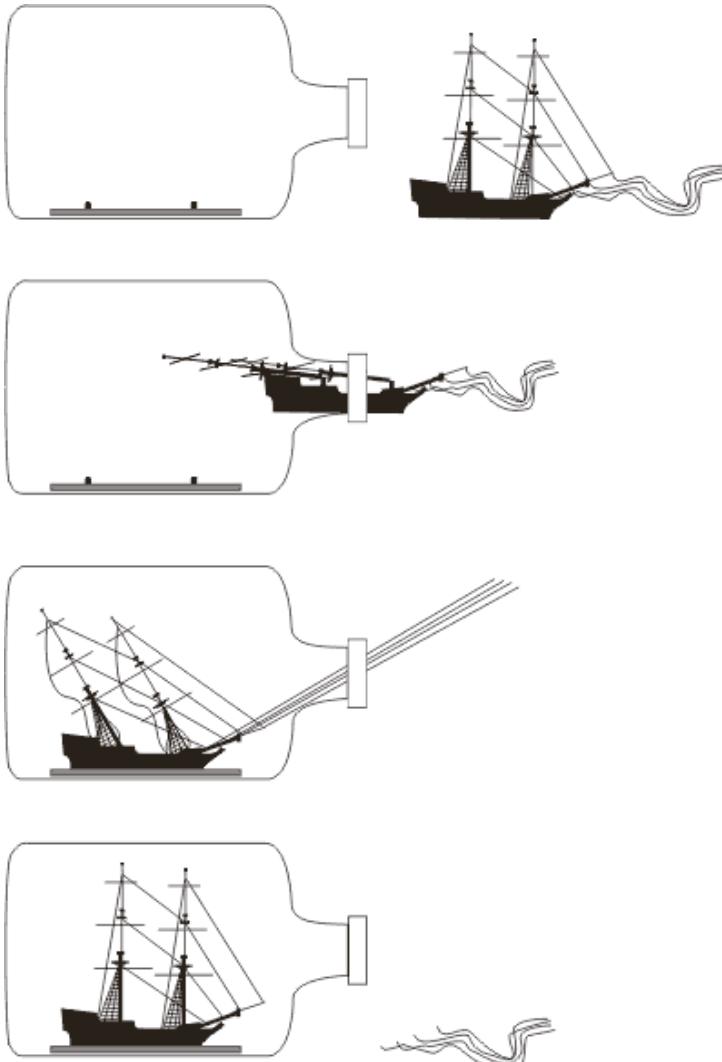




Full-Volume Calibration in KamLAND

The System and its Physics Potential



Karsten M. Heeger, LBNL

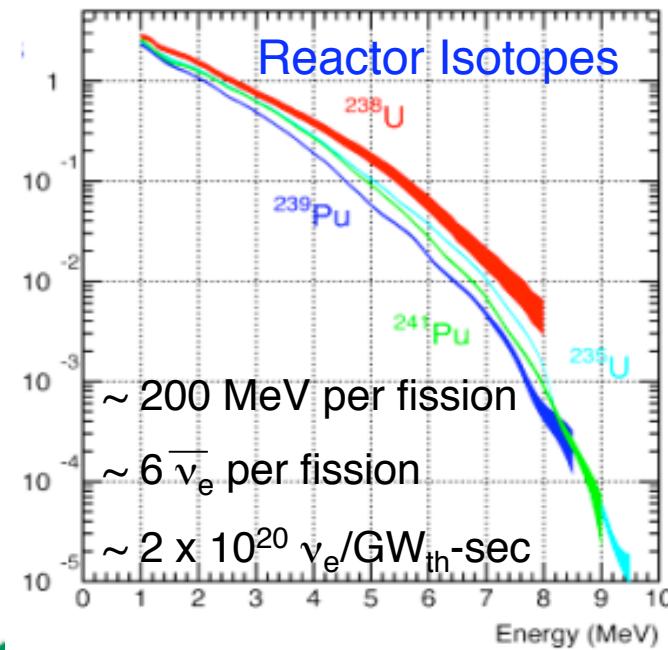
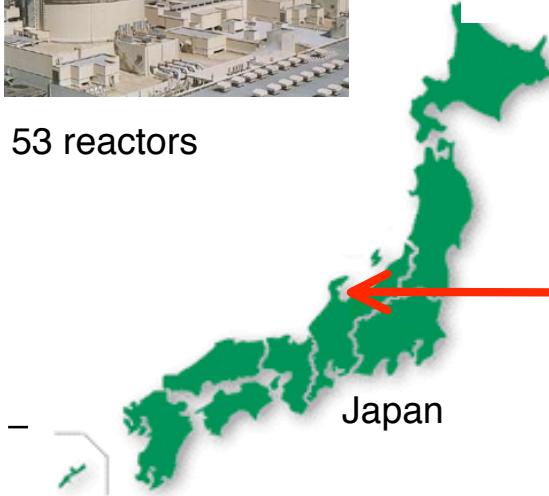
for the KamLAND Collaboration

Measurement of Reactor Anti-Neutrinos in KamLAND

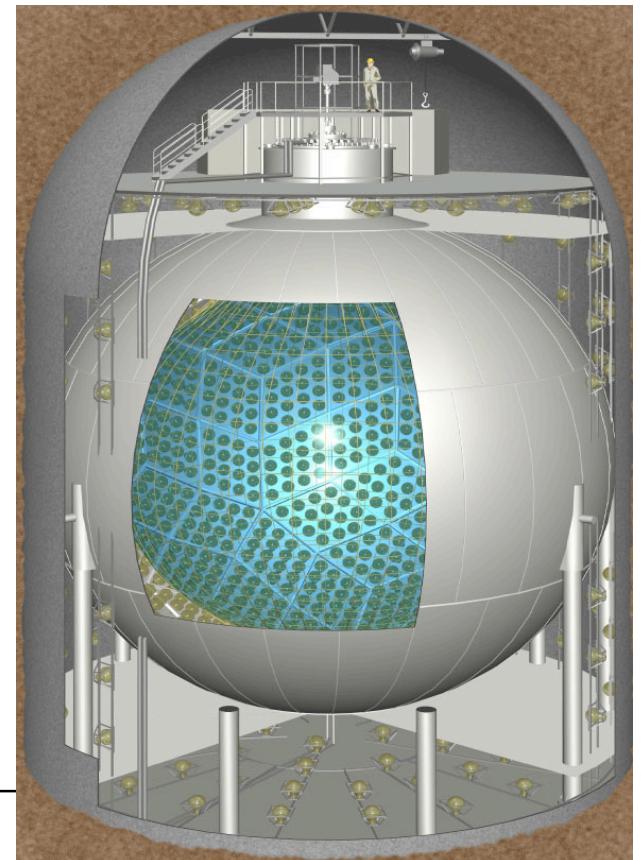
Japanese Reactors



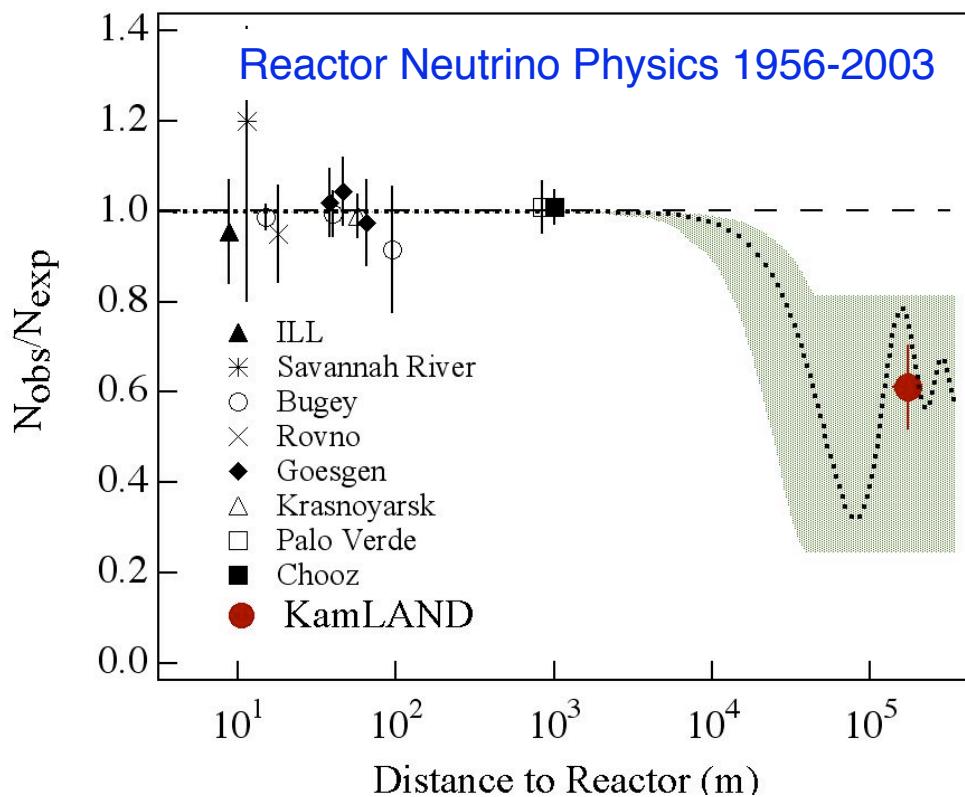
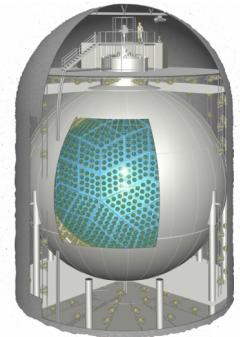
53 reactors



Anti-Neutrino Detection
through inverse β -decay



KamLAND in 2003: First Direct Evidence for Reactor $\bar{\nu}_e$ Disappearance



PRL 90:021802 (2003)

Observed $\bar{\nu}_e$	54 events
No-Oscillation	86.8 ± 5.6 events
Background	1 ± 1 events
Livetime:	162.1 ton-yr



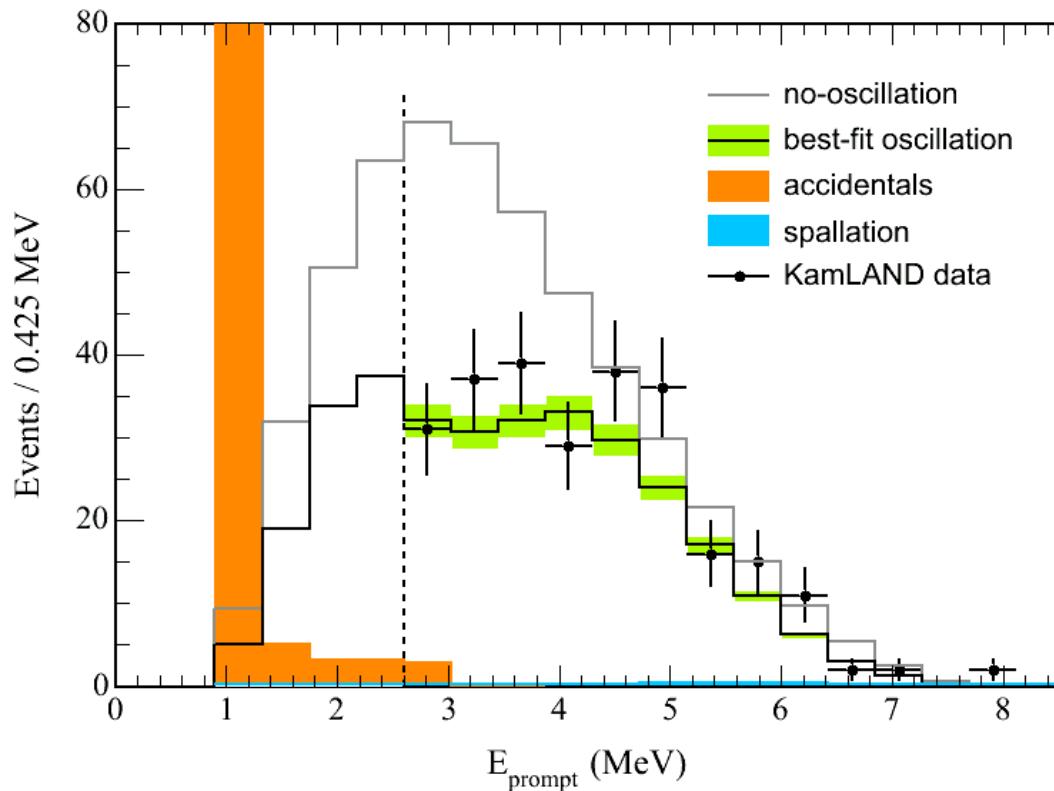
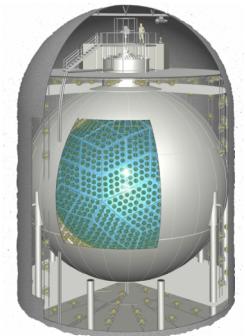
50 Years of Reactor Neutrino Physics

1953 First reactor neutrino experiment

1956 “Detection of Free Antineutrino”,
Reines and Cowan → Nobel Prize in 1995

2003 KamLAND’s observation of $\bar{\nu}_e$
disappearance

KamLAND in 2004: Evidence of Spectral Distortion in Energy Spectrum



hep-ex/0406035 (2004)

Observed $\bar{\nu}_e$	258 events
No-Oscillation	365.2 ± 23.7 (syst.)
Background	17.8 ± 7.3 events
Livetime:	766.3 ton-yr

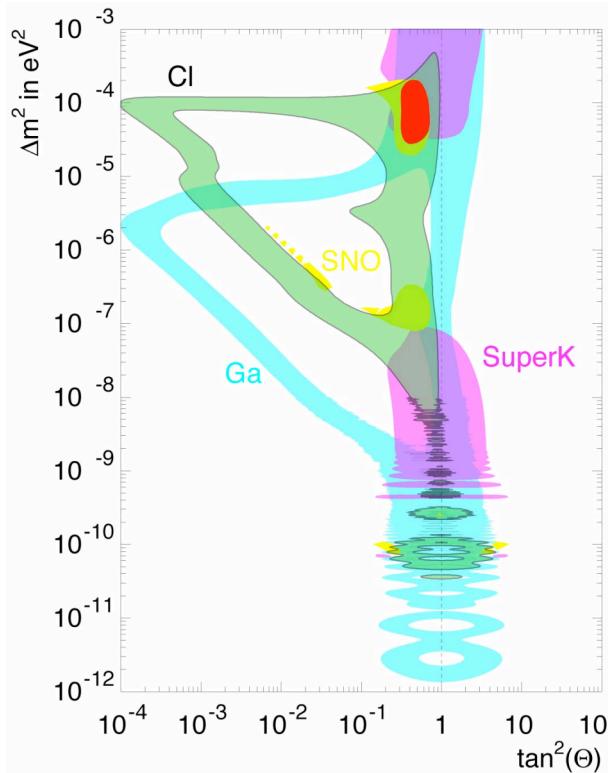
Future: Reduce systematic error
with improved calibrations.

Spectral Distortions: A unique signature of neutrino oscillation!

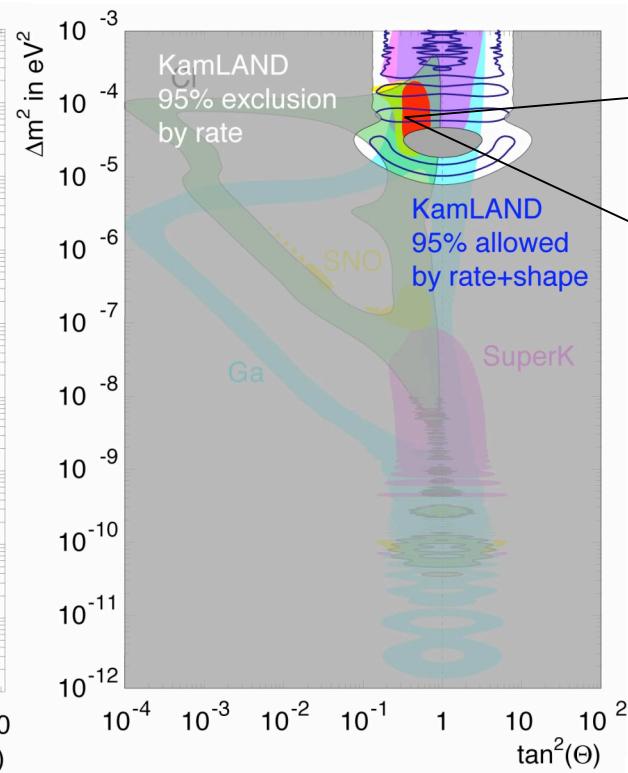
Simple, rescaled reactor spectrum is excluded at 99.6% CL ($\chi^2=37.3/18$)

Measuring Neutrino Oscillation Parameters

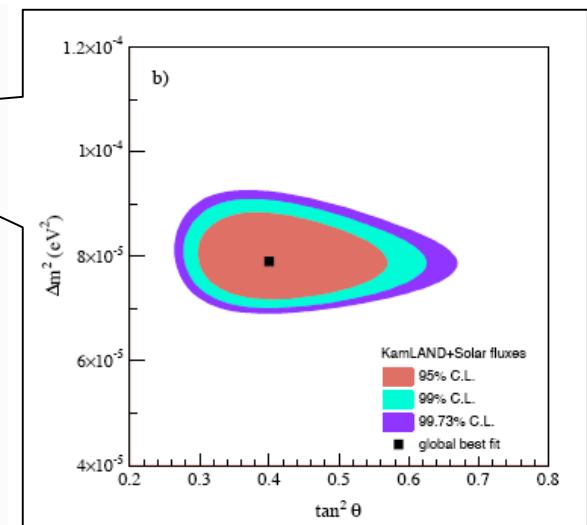
Solar Neutrinos



Solar Neutrinos
+ KamLAND 2003
($\bar{\nu}_e$ rate)



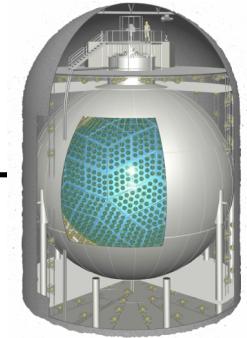
Solar Neutrinos
+ KamLAND 2004
($\bar{\nu}_e$ rate+spectrum)



Agreement between oscillation parameters for $\bar{\nu}$ and ν

Precision neutrino physics

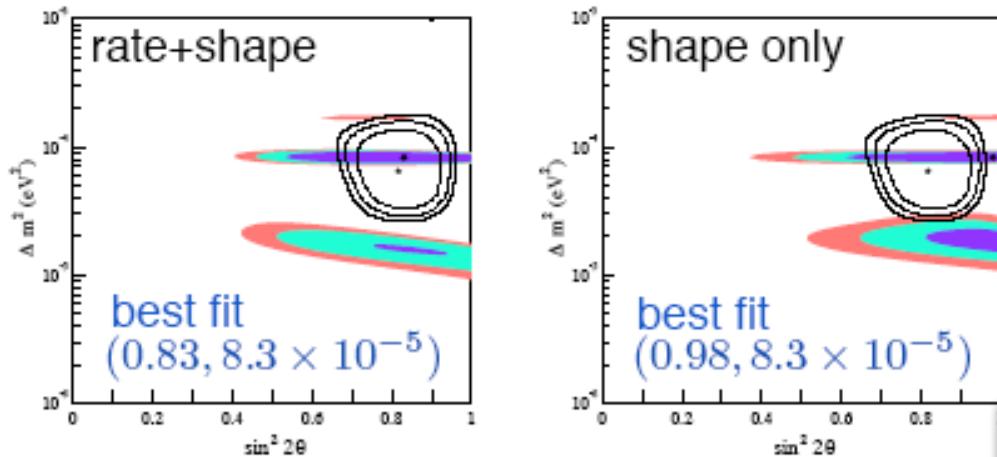
KamLAND - Systematic Uncertainties



E > 2.6 MeV

	%	
Fiducial volume	4.1	• volume calibration
Energy threshold	2.3	• energy calibration or analysis w/out threshold
Cut efficiency	1.6	
Live time	0.06	
Reactor power	2.1	<i>given by reactor company,</i>
Fuel composition	1.0	<i>difficult to improve on</i>
$\bar{\nu}_e$ spectra	2.5	
cross section	0.2	<i>theoretical, model-dependent</i>
Total uncertainty	6.5 %	

Further Improvements on Systematic Errors



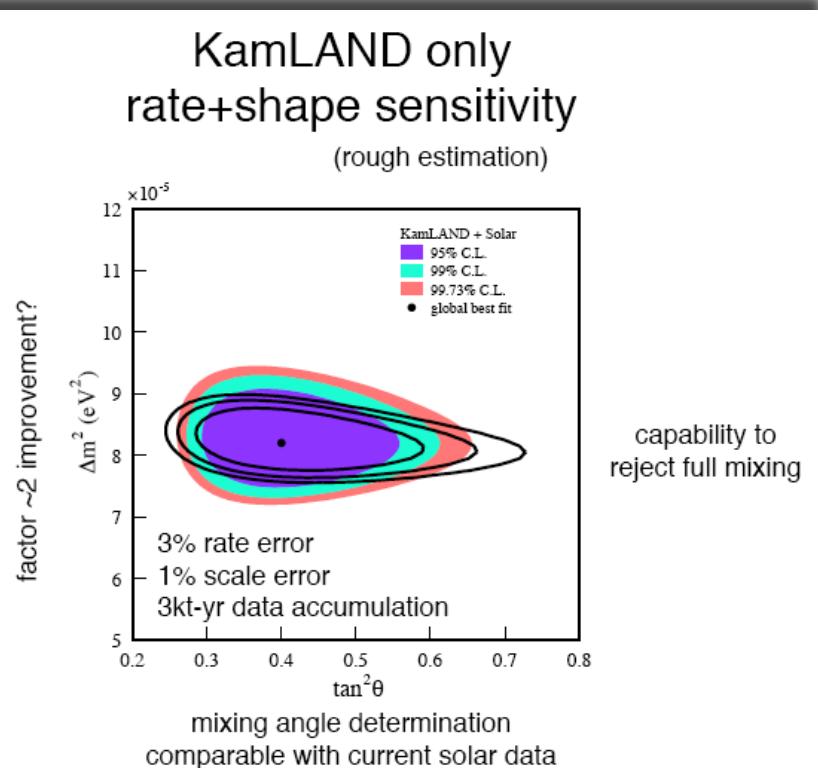
Most constraints from $\bar{\nu}_e$ spectrum due to systematic error on $\bar{\nu}_e$ rate

Systematic limitations:

1. fiducial volume
2. detector response

KamLAND will make most precise determination of Δm_{12}^2 for the foreseeable future.

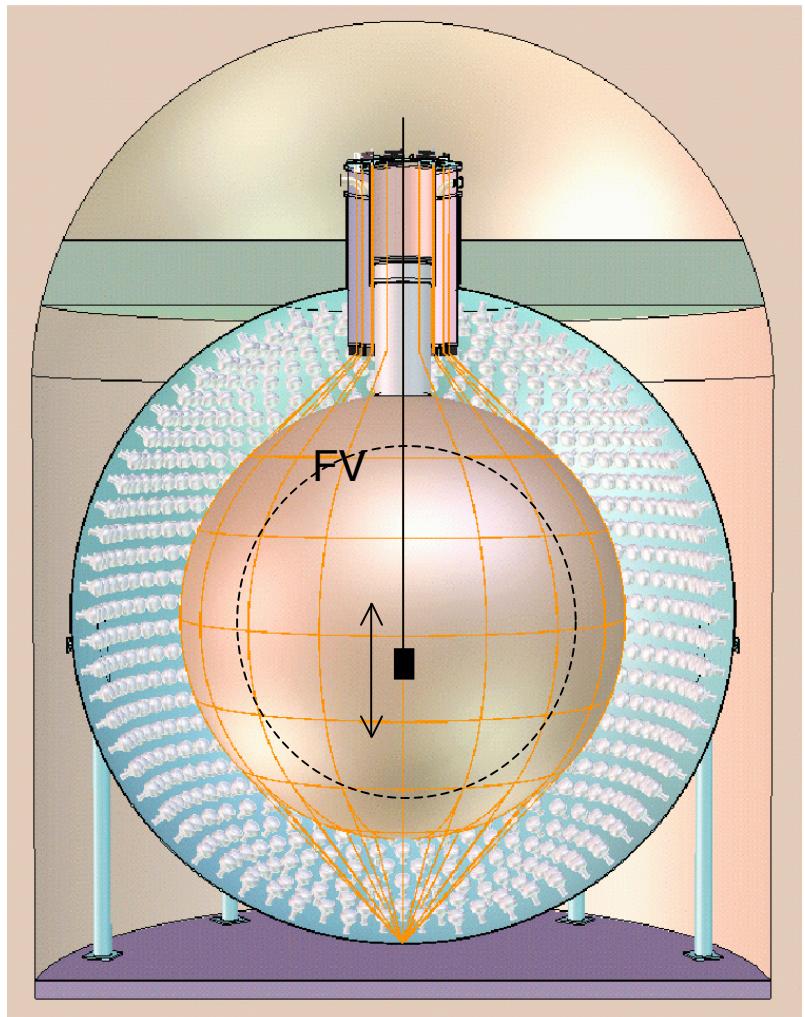
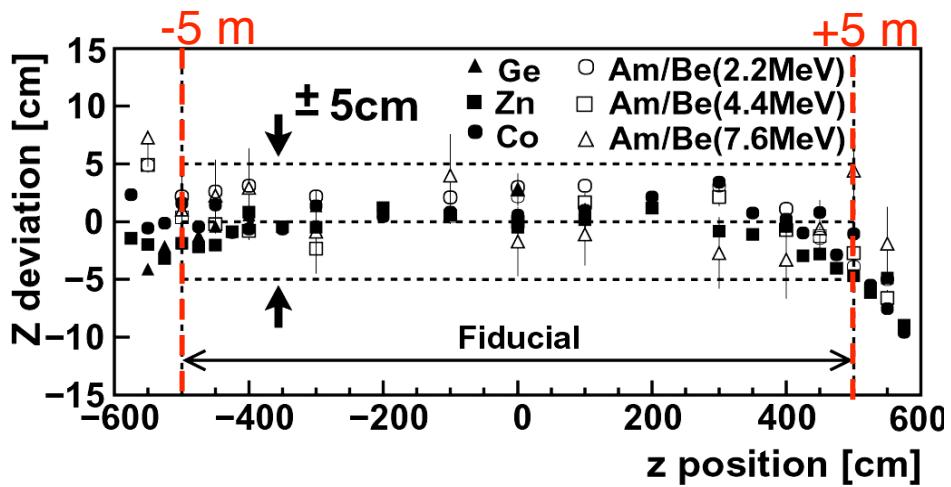
Karsten Heeger, LBNL



KamLAND z-axis Calibration

Routine Calibration Sources

^{68}Ge	e^+	$2 \times 0.511 \text{ MeV}$
^{65}Zn	γ	1.116 MeV
^{60}Co	γ	2.506 MeV
AmBe	γ, n	$2.22, 4.44, \text{ and } 7.65 \text{ MeV}$
Laser and LEDs		



$^{60}\text{Co}: 1.173+1.333 \text{ MeV in the detector}$

$$\sigma = 6.2\% / \sqrt{E}$$

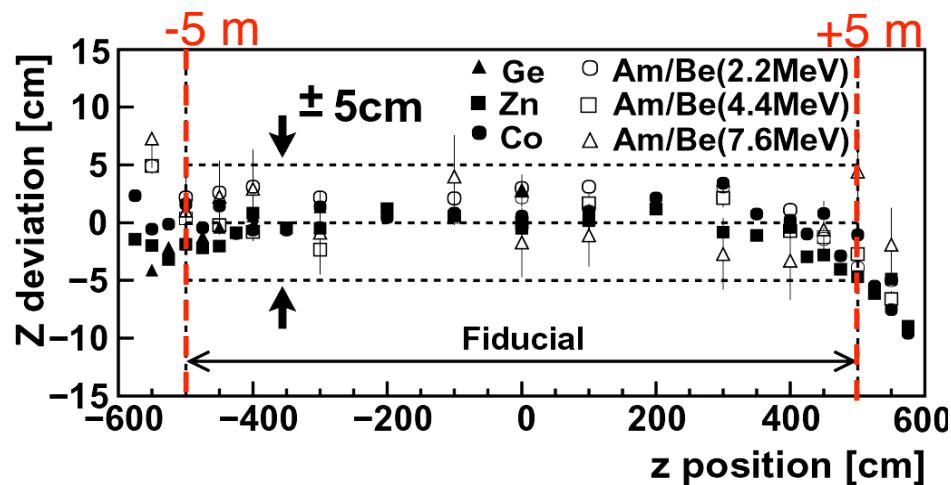
light yield: 239 p.e./MeV

KamLAND z-axis Calibration

Routine Calibration Sources

^{68}Ge e^+ $2 \times 0.511 \text{ MeV}$
 ^{65}Zn γ 1.116 MeV
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AmBe γ, n $2.22, 4.44, \text{ and } 7.65 \text{ MeV}$

Laser and LEDs

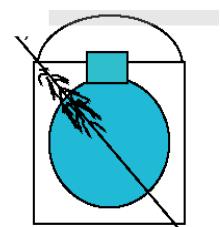
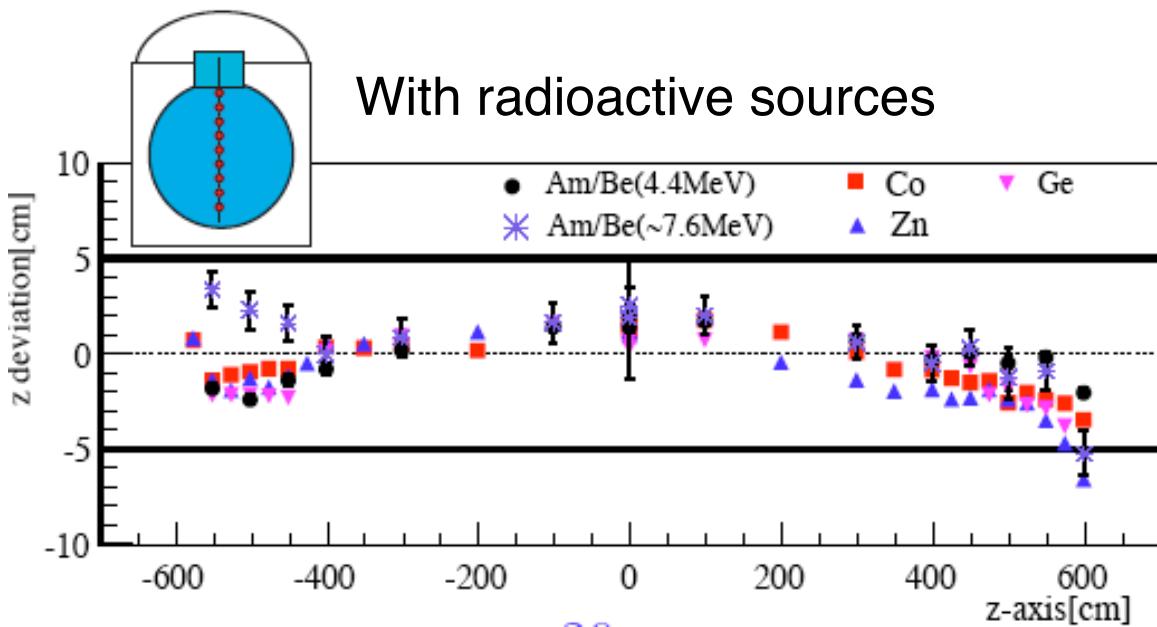
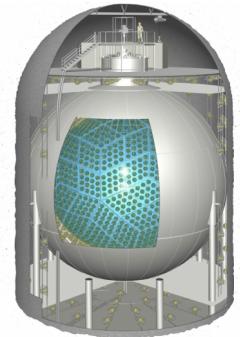


$^{60}\text{Co}: 1.173+1.333 \text{ MeV in the detector}$

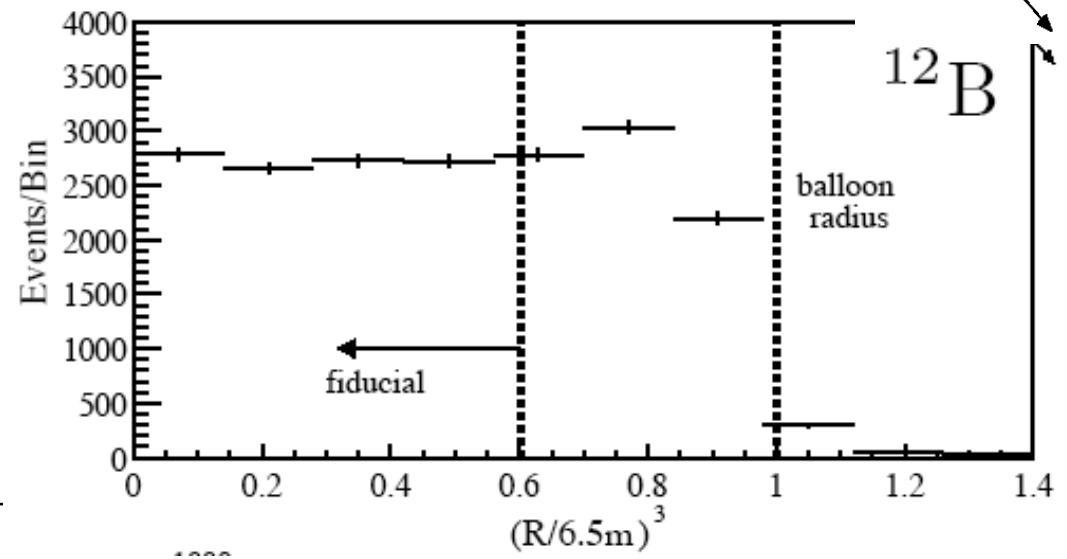
$$\sigma = 6.2\% / \sqrt{E}$$

light yield: 239 p.e./MeV

Fiducial Volume Determination



With muon spallation

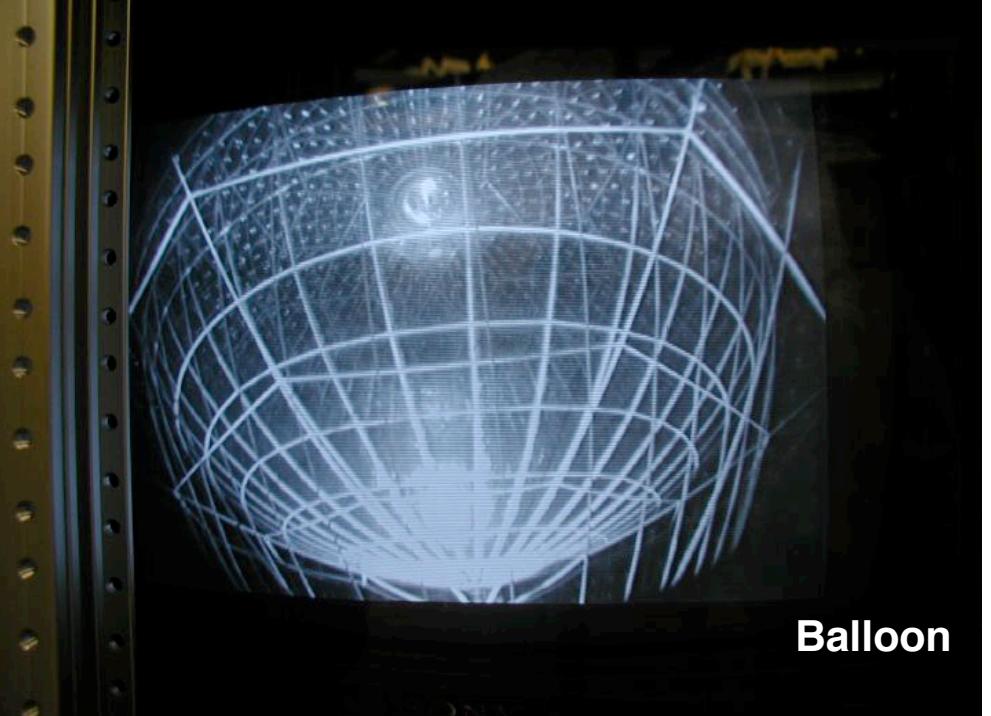
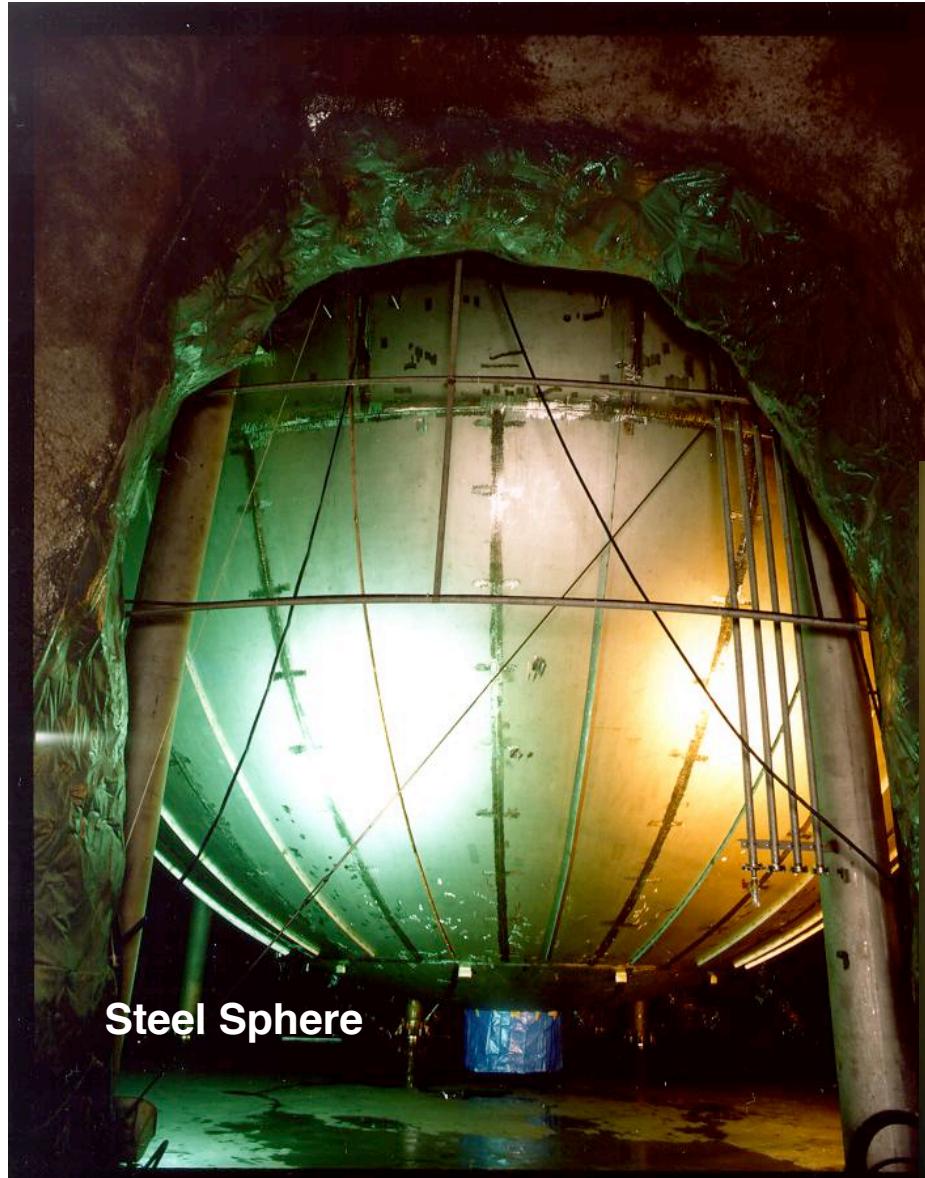


Fiducial/Total Volume Ratios

Geometrical	0.595 ± 0.013
^{12}B	0.607 ± 0.006
$p(n,\gamma)\text{d}$	0.587 ± 0.013
^9Li relative	< 2.7%

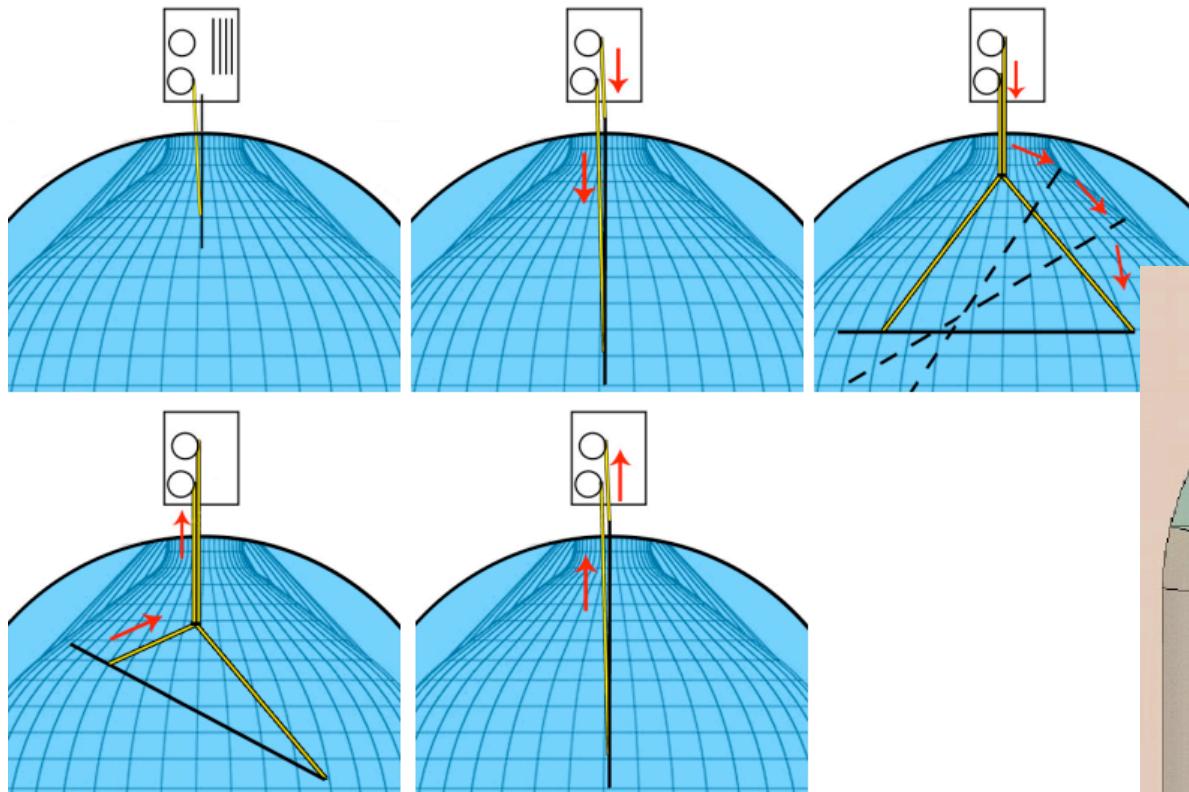
KamLAND volume error: 4.7%

KamLAND



KamLAND Full-Volume Calibration

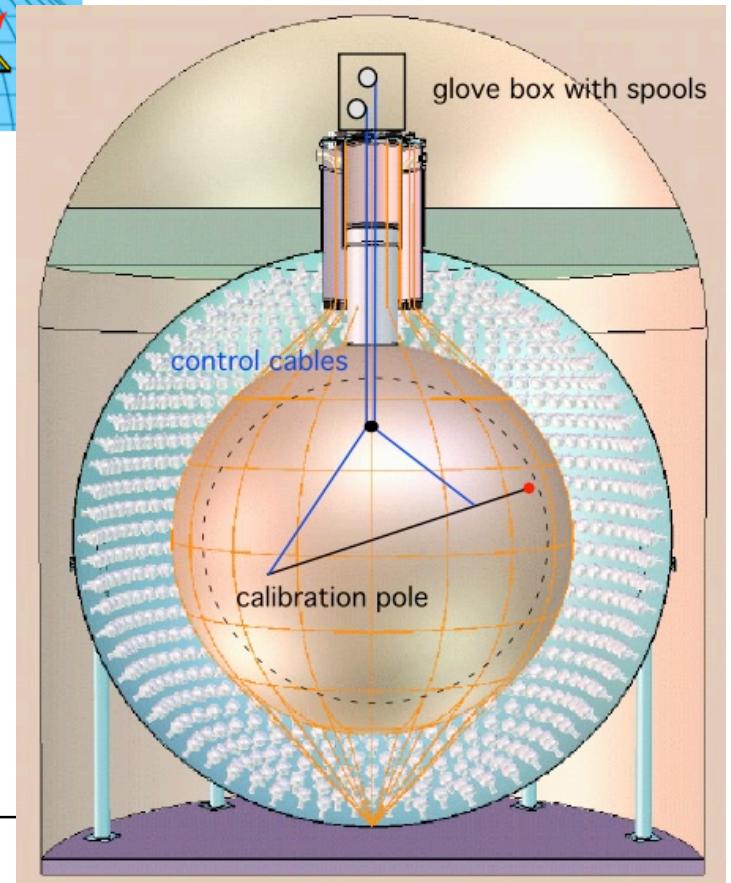
Calibration throughout entire detector volume



Fiducial volume: $R < 5.5$ m

$$\Delta R_{FV} = 5 \text{ cm} \rightarrow \Delta V = 2.7\%$$

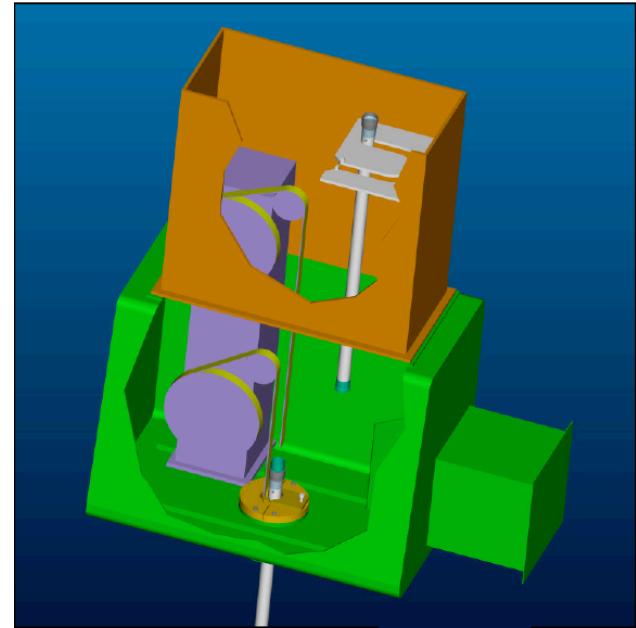
$$\Delta R_{FV} = 2 \text{ cm} \rightarrow \Delta V = 1.1\%$$



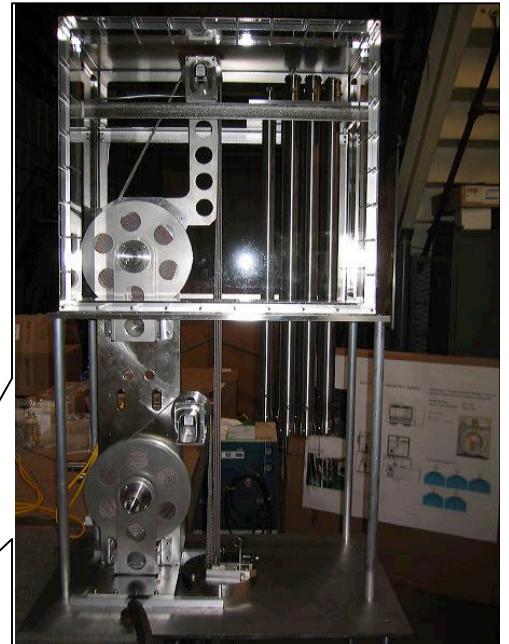
Position Dependence of Detector Response

Event energy
Vertex reconstruction

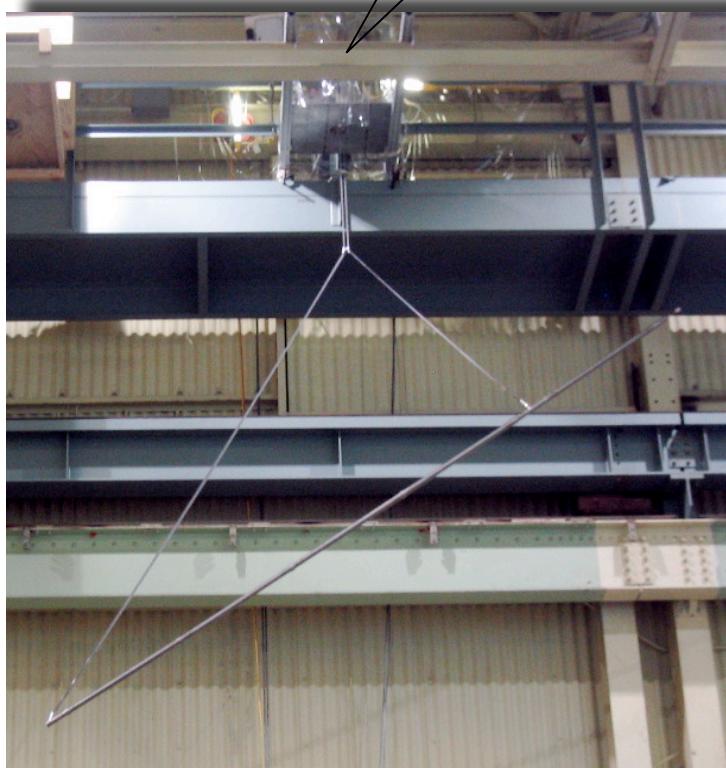
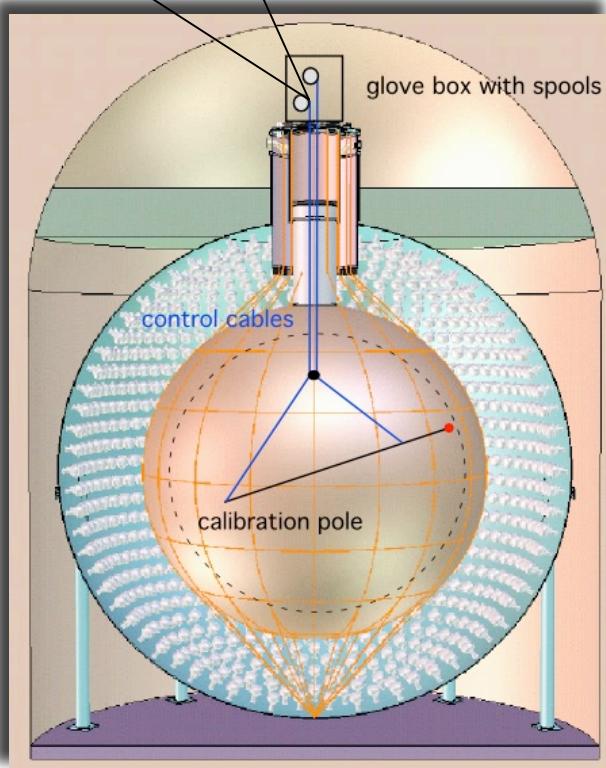
$$E(r, \theta, \phi)$$
$$R_{fit}(r, \theta, \phi)$$



Construction of a Full-Volume Calibration System

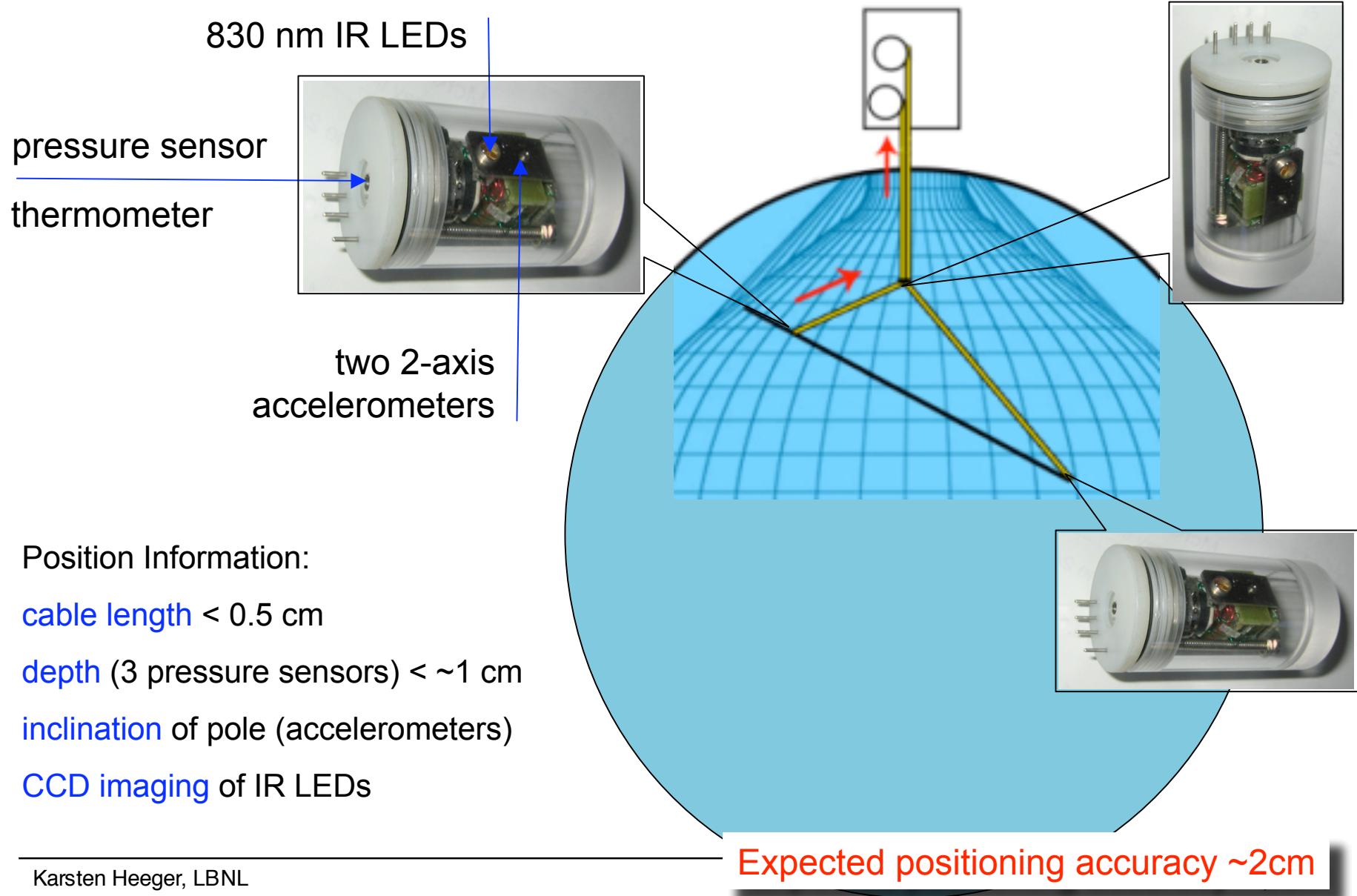


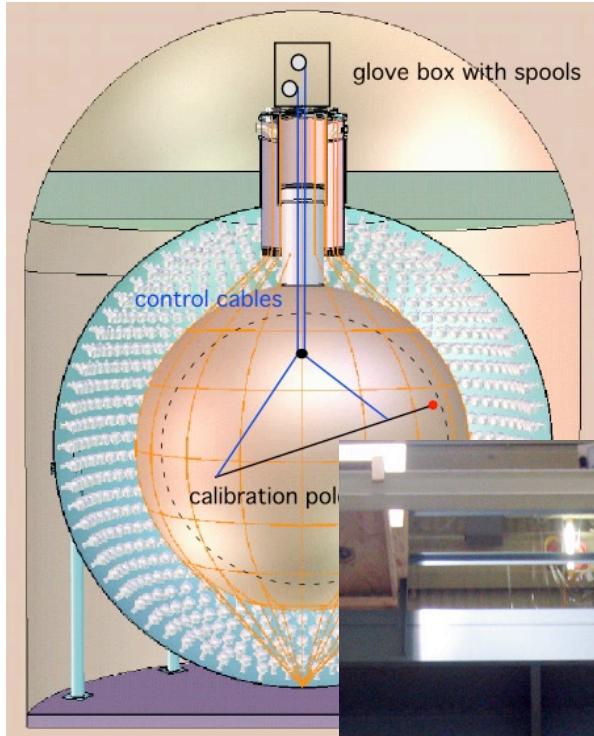
Fall 2003



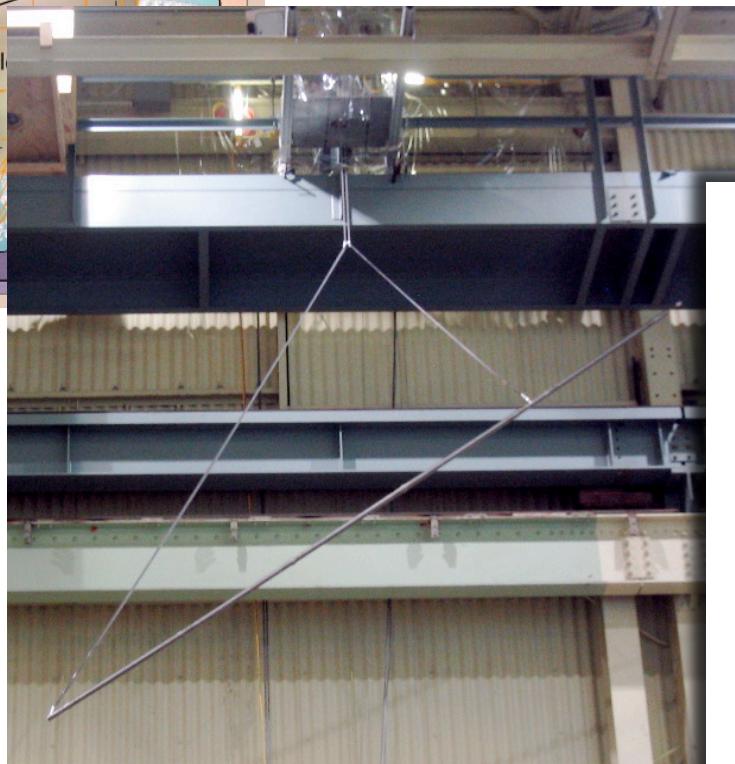
Fall 2004

Instrumentation of the Calibration System



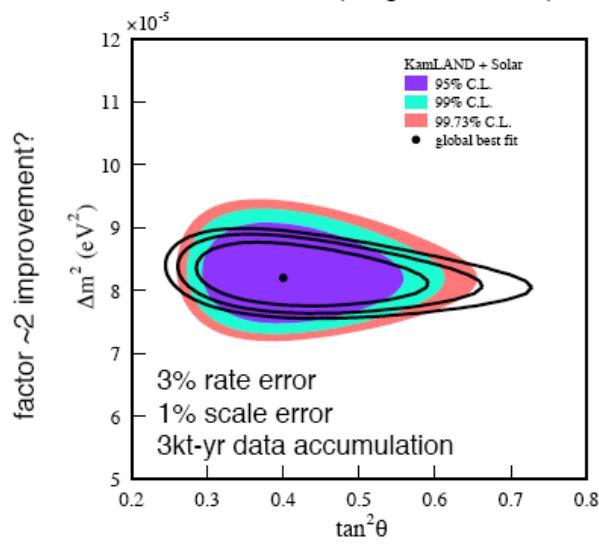


Designed and built a full-volume calibration system for KamLAND



Commissioning in early 2005
Last major detector upgrade for KamLAND

KamLAND only
rate+shape sensitivity
(rough estimation)



Will reduce KamLAND's systematic uncertainty on the fiducial volume and improve its sensitivity to Δm_{12}^2 .

mixing angle determination
comparable with current solar data

KamLAND Collaboration



G.A.Horton-Smith, R.D.McKeown, J.Ritter, B.Tipton,
P.Vogel

California Institute of Technology

C.E.Lane, T.Miletic
Drexel University

Y-F.Wang
IHEP, Beijing

T.Taniguchi
KEK

B.E.Berger, Y-D.Chan, M.P.Decowski, D.A.Dwyer,
S.J.Freedman, Y.Fu, B.K.Fujikawa, K.M. Heeger,
K.T.Lesko, K-B.Luk, H.Murayama, D.R.Nygren,
C.E.Okada, A.W.Poon, H.M.Steiner, L.A.Winslow
LBNL/UC Berkeley

S.Dazeley, S.Hatakeyama, R.C.Svoboda
Louisiana State University

J.Detwiler, G.Gratta, N.Tolich, Y.Uchida
Stanford University

K.Eguchi, S.Enomoto, K.Furuno, Y.Gando, J.Goldman,
H.Ikeda, K.Ikeda, K.Inoue, K.Ishihara, T.Iwamoto,
T.Kawashima, Y.Kishimoto, M.Koga, Y.Koseki,
T.Maeda, T.Mitsui, M.Motoki, K.Nakajima, H.Ogawa,
K.Oki, K.Owada, I.Shimizu, J.Shirai, F.Suekane,
A.Suzuki, K.Tada, O.Tajima, K.Tamae, H.Watanabe
Tohoku University

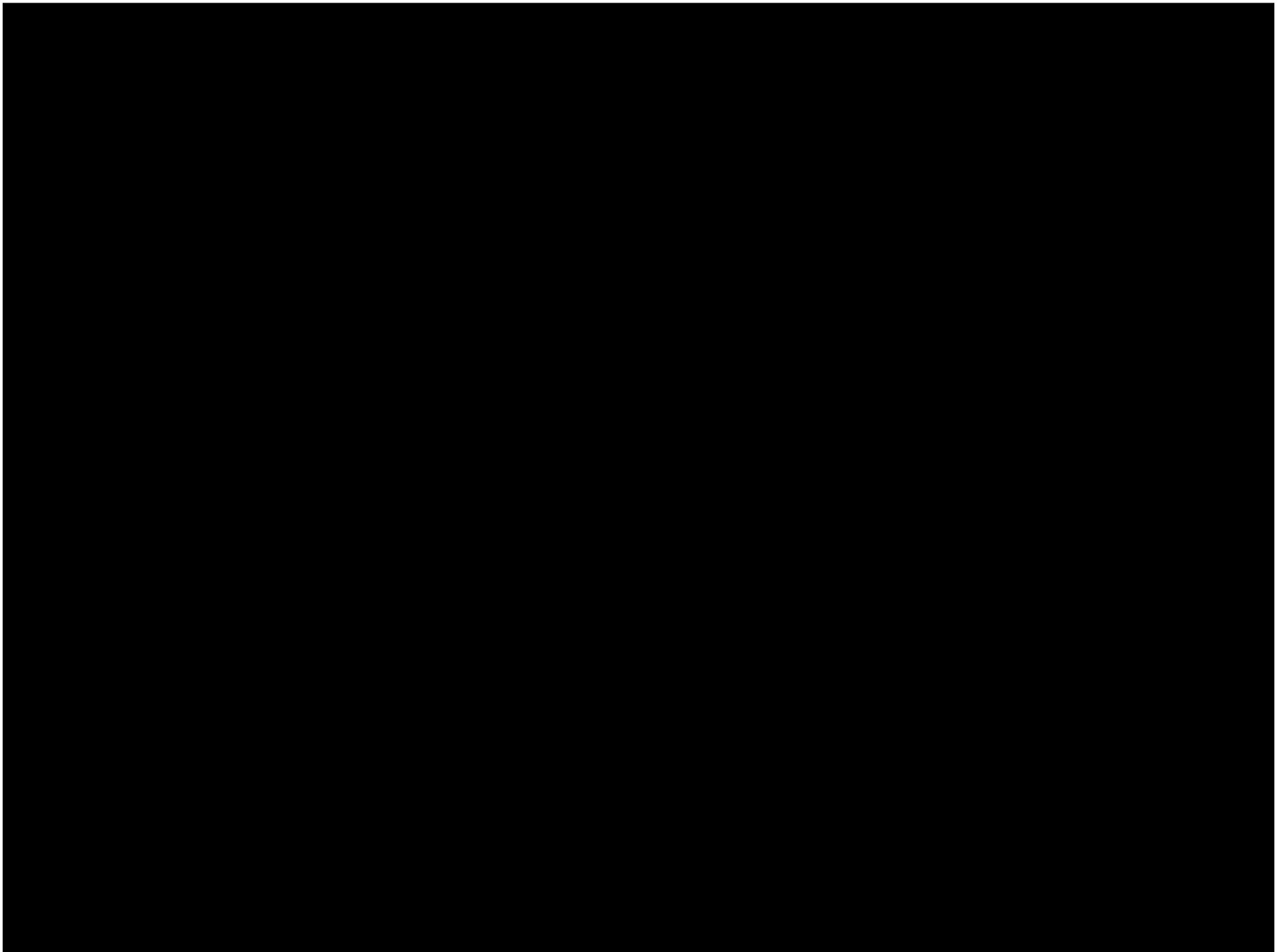
L.DeBraeckeleer, C.Gould, H.Karwowski, D.Markoff,
J.Messimore, K.Nakamura, R.Rohm, W.Tomow,
A.Young
TUNL

J.Busenitz, Z.Djurcic, K.McKinny, D-M.Me, A.Piepke,
E.Yakushev
University of Alabama

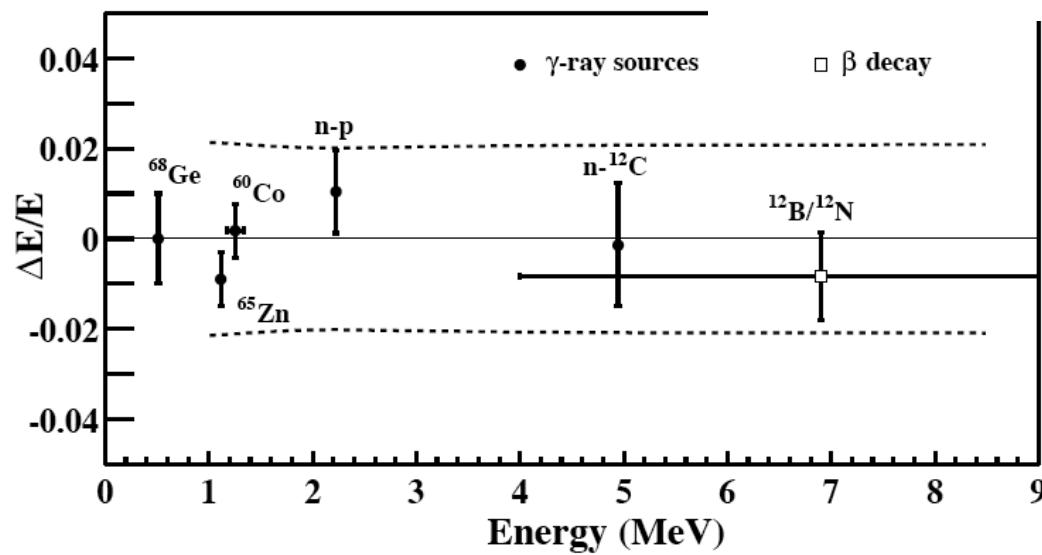
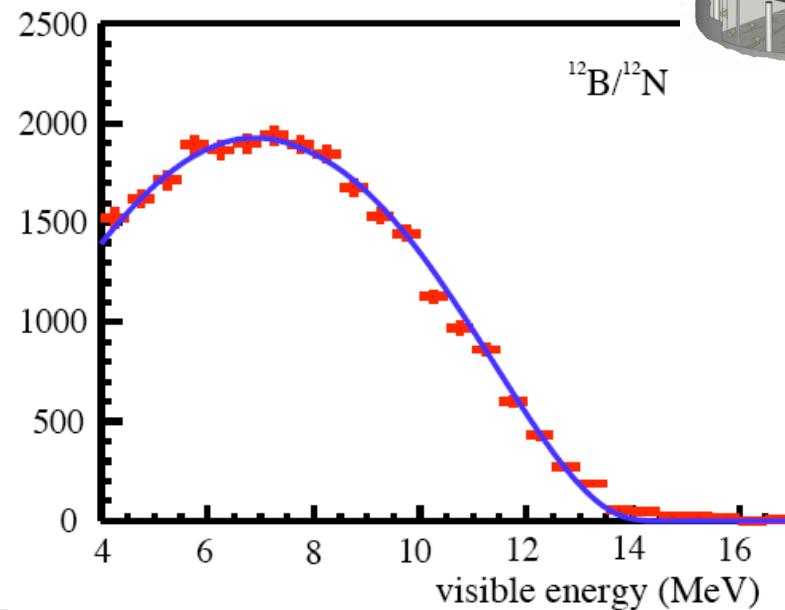
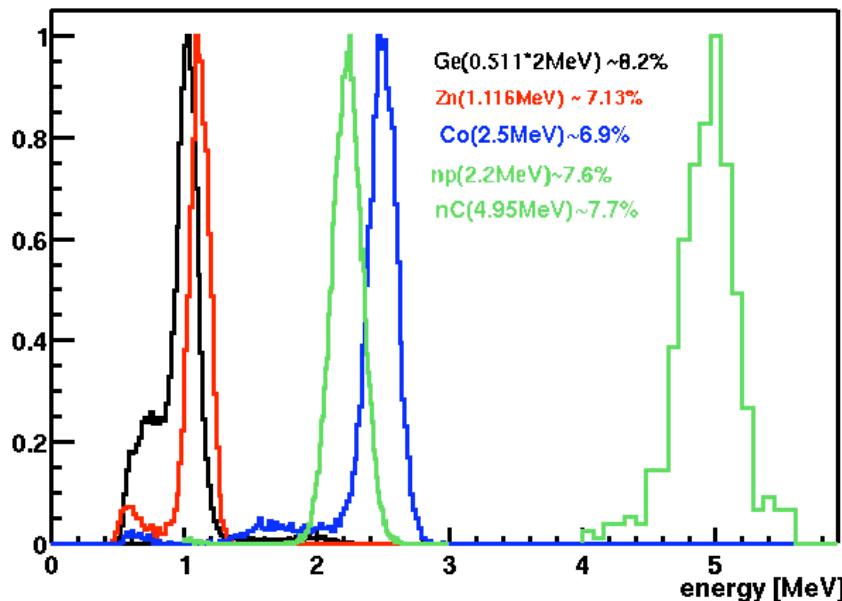
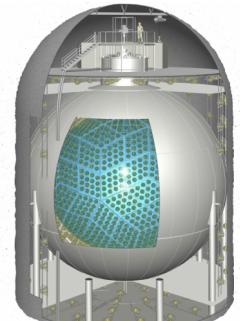
P.Gorham, J.Leamed, J.Maricic, S.Matsuno, S.Pakvasa
University of Hawaii

B.D.Dieterle
University of New Mexico

M.Batygov, W.Bugg, H.Cohn, Y.Efremenko,
Y.Kamyshkov, Y.Nakamura
University of Tennessee



Detector Energy Scale and Response



October 29, 2004